PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering – Port Said University
Volume (21) No. (2) September 2017 pp. 62:67

# Assessment of Centrifugal Motion Effect on GNSS Receiver Measurements

Ahmed M Amin[1], Ahmed I El-Hattab[2] and Hassan M Fathallah[3]

## Abstract

Determining the three dimensional coordinates of points by communication with satellites has always inspired scientists and researchers. Primarily, GNSS were used in a static or semi static mode if high accuracy is required. However, as a result of the substantial improvement made in the capabilities of the satellites and the signal structure, it was important to investigate methods of improving the accuracy obtained from these systems when used in high dynamic environment which is of great importance for many applications. The purpose of this research is to investigate how far GNSS receivers could be used in such high dynamic applications and what will be the resulting accuracy. A test rig has been specifically manufactured to produce centrifugal motion to simulate the GNSS movements when used in high dynamic mode such as unmanned vehicles, ground motion during natural hazards or movements of high-rise building. The accuracy of the GNSS receiver was measured considering different parameters such as baseline length, radius of rotation and processing software. Also, the lose-of- signal lock was detected in each case. The research revealed that the GNSS receiver has very promising potential for use in high dynamic applications.

**Keywords:** *High Dynamic Applications; GNSS Receivers; Horizontal Test Rig.*

## 1. Introduction

Determining accurate three dimensional coordinates of points by GNSS has always been the focus of many scientists and researchers. Positioning systems by satellites began in the early sixties of the last century. Transit, Dopplar satellites and Navstar are early systems developed for that purpose. These systems were capable of determining the position of point's reference to a selected coordinate system at anytime, anywhere and at any weather by communicating with a number of satellites orbiting the planet. The development of these positioning systems is nowadays called Global Navigation Satellite Systems (GNSS).

Primarily, GNSS were used in a static mode if high accuracy is required. However, as a result of the substantial improvement made in the capabilities of the satellites and the signal structure, it was important to investigate methods of assessing the accuracy obtained from these systems when used in high dynamic environment which is of great importance for many applications. An example of these applications is the controlling of transportation vehicle to be fully automatic (unmanned) such as cars, trains and planes. Such applications require a reliable positioning system which provides high accuracy when the receiver is onboard a platform moving at a very high speed [1].

[1]*Professor of Surveying and Photogrammetry, Faculty of Engineering, Suez Canal University, Ismailia, Egypt, E-mail:* Profahmedamin@yahoo.com

[2]*Professor of Surveying and Geodesy, Faculty of Engineering, Port Said University, Port Said, Egypt, E-mail:* Dr.ahmed.elhattab@gmail.com

[3]*Instructor & MSc student at Civil Eng. Dept., Faculty of Engineering, Suez Canal University, Ismailia, Egypt, E-mail:* hassan_fathallah@eng.suez.edu.eg

Monitoring the ground motion during natural hazards such as Earthquakes and Tsunami is another field for GNSS applications [2]. Also the monitoring of lateral and torsional displacements of high rise buildings or bridges with long spans has been an interesting field whether for observing and maintaining or for modeling this motion for analysis and design [3].

Thus, there is a plenty of applications in which high dynamic GNSS can play an important role or being an alternative solution instead of other traditional measuring techniques.

The objective of this research is to assess the behavior of GNSS sensors when used in high dynamic environments. For this reason, a test rig was especially designed and manufactured on which the positioning system was mounted and used to measure the motions and displacements under different operating parameters such as speed and baseline length with a view to reach a conclusion as to how far the GNSS sensors could be used in such applications. In addition, data processing was made using three different software packages and the results were compared.

## 2. Testing Method

A test rig was specifically designed and manufactured at the Suez Canal University lab. The rig was designed so that the GNSS receiver may rotate in the horizontal plan at selected speeds. The rig comprises an electric motor and a rotating lever which carries the receiver and the balancing weight to reduce the vibrations resulted from the rotation of the receiver, the radius of rotation of both receiver and balancing mass can be changed to be 15, 30 or 45 cm.

.

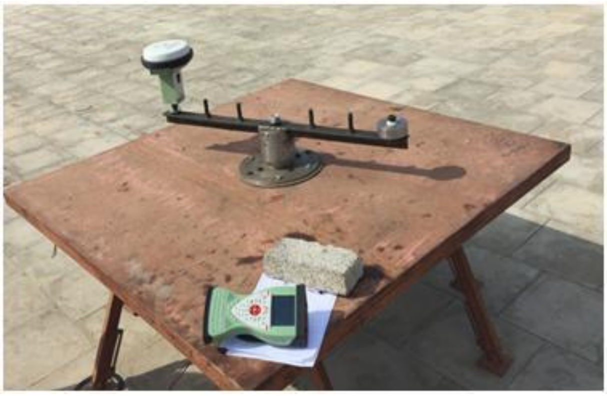


**Figure 1: Overview of the manufactured rig**

The different parameters which were varied during the tests are:

**(a) Speed:** The speed was the main factor since the aim of the research was to assess the behavior of the GNSS receiver in high dynamics mode. A variable frequency drive (VFD) inverter from LSIS Co. was used to control the speed of rotation and the model used was iC5.

**(b) Diameter:** The rig was designed to allow for the rotation at 3 different diameters. These rotation diameters were 30, 60 and 90 cm. These values were selected based on research survey which showed that tall buildings and long span bridges are allowed to sway horizontally in similar range of values with a maximum of 2 m. For example, the World Trade Center in USA swayed three feet (90 cm) [4] and Burj Khalifa in Dubai swayed about 2 meters [5].

**(c) Baseline length:** The GNSS receiver was tested on two different baselines. The first was about 60 meters length which may be considered short and the other was about 2 km which may be considered medium [6].

**(d) Processing software:** Data processing packages vary in their computational models and capabilities. In this research, three different commercial software packages were used to test the collected data, these are:

(i) Leica Geo Office (LGO) package Version 8.3. This Package is provided with the GNSS system used in the current research work.
(ii) Trimble Business Center (TBC) version 3.5.
(iii) RTKLIB version V 2.4.2 (open source)

The tests were conducted as follows:

1. The GNSS rover receiver was set upon the roof of the Faculty of Engineering building, Suez Canal University. The short base line test was made by allowing the rig to rotate at 15 cm diameter while the base receiver was set up at a station about 60 m away.
2. The rig was left rotating for five minutes continuously at the lowest speed which is 0.18 m/sec for this radius.
3. The test was repeated with increasing the speed to the next level. The increment in the speed for this radius was 0.18 m/sec for each trial.
4. This increment in the speed was applied several times till the receiver lost signal at a particular speed defined as the maximum speed which was 9.9 m/sec.
5. The above steps were repeated by changing the various parameters (rotation radius 30 cm and 45 cm).
6. Steps 1 to 5 were repeated for the medium baseline length where the base receiver was set up at a station about 2 km away.
7. In total, 59 tests were carried out.

In all tests, observations were collected with a rate of 20 Hz. A data storage mechanism was adopted to store the raw data using coding system to avoid mixing the observations and to ease the retrieve of the data.

The data was collected in two modes, post processing and RTK. In the post processing mode, the data was analyzed to compare between different software packages, rotation radii and baseline lengths at different rotation speeds. In case of RTK mode, the accuracy of the receiver was obtained at different rotation radii and at each baseline length. In this test, the same procedure outlined above was repeated, however, the rotation speed was increased every two minutes till losing lock and without stopping the rig motion.

## 3. Data Processing and Analysis

The measured radius was calculated according to the following equation:

$$R_i = (\Delta X_i^2 + \Delta Y_i^2)^{1/2} \qquad (1)$$

Where the $R_i$ is the measured radius of rotation at time epoch (i).

$\Delta X_i$ and $\Delta Y_i$ are the differences between horizontal coordinates of the center of rotation and the receiver's position at time epoch (i).

Then the value of error at the same time epoch equal:

$$\Delta R = R_r - R_i \qquad (2)$$

Where $R_r$ is the real radius of rotation.

These values were computed at each time epoch for every test. Then the root mean square (RMS) of each test was calculated. The resolved position of some points at some tests was far from the center of rotation by twice the radius. These points were removed from RMS calculation and defined as outlier points.

**(a) Post processing mode**

For each test, the speed of rotation, which simulates the speed of motion of the platform carrying the GNSS, was increased until the receiver lost locking (maximum speeds). These maximum speeds are listed in Table 1 for each diameter and at each baseline.

**Table 1: Maximum speed obtained at each radius and baseline**

| Post Processing Mode Tests | Trial (1) – During Short Baseline | | Trial (2) – During Medium Baseline | |
|---|---|---|---|---|
| | Km/h | RPM | Km/h | RPM |
| 45 cm radius | 13.464 | 79.33 | 12.276 | 72.33 |
| 30 cm radius | 10.03 | 88.67 | 9.504 | 84 |
| 15 cm radius | 9.9 | 175 | 9.24 | 163.33 |

The speeds listed in table 1 are the arithmetic average of many trials and they are within ±5 RPM tolerance. This is because losing of lock depends on many factors such as the presence of obstacles, number of satellites, satellites conditions and dilution of precision (DOP) [7].

Due to the huge amount of data collected on short baseline tests, only samples are listed below in tables 2 and 3 .

**Table 2: RMS of Horizontal components**

| Radius | RPM | RMS (H) | | |
|---|---|---|---|---|
| | | LGO | TBC | RTKLIB |
| 45 | 11.67 | 0.0048 | 0.0059 | 0.0055 |
| | 23.33 | 0.0042 | 0.0038 | 0.0035 |
| | 35 | 0.0039 | 0.0032 | 0.0035 |
| | 46.67 | 0.0039 | 0.005 | 0.0047 |
| | 58.33 | NONE | 0.012 | 0.0171 |
| | 70 | NONE | 0.0044 | 0.0394 |
| | 79.33 | NONE | 0.0149 | 0.0179 |
| 30 | 11.67 | 0.0038 | 0.0043 | 0.0039 |
| | 23.33 | 0.0048 | 0.005 | 0.0071 |
| | 35 | 0.0026 | 0.0033 | 0.0099 |
| | 46.67 | 0.0066 | 0.0065 | 0.0075 |
| | 58.33 | NONE | 0.0081 | 0.149 |
| | 70 | NONE | 0.0116 | 0.191 |
| | 81.67 | NONE | 0.0042 | 0.056 |
| | 88.67 | NONE | 0.0079 | 0.079 |
| 15 | 11.67 | 0.0041 | 0.0029 | 0.0035 |
| | 23.33 | 0.0132 | 0.0039 | 0.0034 |
| | 35 | 0.0134 | 0.0031 | 0.0029 |
| | 46.67 | 0.0229 | 0.0022 | 0.0024 |
| | 58.33 | NONE | 0.0032 | 0.0046 |
| | 70 | NONE | 0.0028 | 0.0093 |
| | 81.67 | NONE | 0.0025 | NONE |
| | 93.33 | NONE | 0.0077 | 0.0302 |
| | 105 | NONE | 0.0036 | 0.0116 |
| | 116.67 | NONE | 0.0048 | 0.0081 |
| | 128.33 | NONE | 0.004 | 0.0073 |
| | 140 | NONE | 0.0094 | NONE |
| | 151.67 | NONE | 0.0049 | 0.019 |
| | 163.33 | NONE | 0.0035 | 0.0139 |
| | 175 | NONE | 0.0052 | 0.0246 |

**Table 3: RMS of Vertical components**

| Radius | RPM | RMS (H) | | |
|---|---|---|---|---|
| | | LGO | TBC | RTKLIB |
| 45 | 11.67 | 0.0082 | 0.0078 | 0.0087 |
| | 23.33 | 0.0075 | 0.0061 | 0.0083 |
| | 35 | 0.0063 | 0.0074 | 0.0072 |
| | 46.67 | 0.0069 | 0.0045 | 0.0082 |
| | 58.33 | NONE | 0.0122 | 0.008 |
| | 70 | NONE | 0.0035 | 0.1992 |
| | 79.33 | NONE | 0.0558 | 0.1247 |
| 30 | 11.67 | 0.0046 | 0.0051 | 0.006 |
| | 23.33 | 0.0133 | 0.012 | 0.0091 |
| | 35 | 0.0064 | 0.0065 | 0.0066 |
| | 46.67 | 0.0095 | 0.0092 | 0.0081 |
| | 58.33 | NONE | 0.027 | 1.04 |
| | 70 | NONE | 0.0119 | 2.82 |
| | 81.67 | NONE | 0.014 | 1.1 |
| | 88.67 | NONE | 0.017 | 2.37 |
| 15 | 11.67 | 0.0038 | 0.0039 | 0.005 |
| | 23.33 | 0.004 | 0.0036 | 0.0036 |
| | 35 | 0.0058 | 0.0041 | 0.0042 |
| | 46.67 | 0.0106 | 0.0041 | 0.0043 |
| | 58.33 | NONE | 0.0026 | 0.0043 |
| | 70 | NONE | 0.0022 | 0.0447 |
| | 81.67 | NONE | 0.002 | NONE |
| | 93.33 | NONE | 0.0071 | 0.1011 |
| | 105 | NONE | 0.0029 | 0.0498 |
| | 116.67 | NONE | 0.009 | 0.208 |
| | 128.33 | NONE | 0.0081 | 0.0087 |
| | 140 | NONE | 0.0026 | NONE |
| | 151.67 | NONE | 0.0134 | 0.173 |
| | 163.33 | NONE | 0.0049 | 0.1136 |
| | 175 | NONE | 0.0041 | 0.176 |

As mentioned earlier, many parameters were investigated like processing software, radius of rotation, baseline length and speed of rotation. So, the effect of each parameter was studied.

**I. The effect of processing software packages**

Sample graphs were plotted in figure (2) to show the effect of processing software on the accuracy.

A)

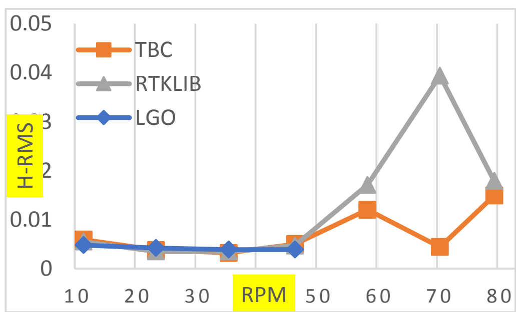
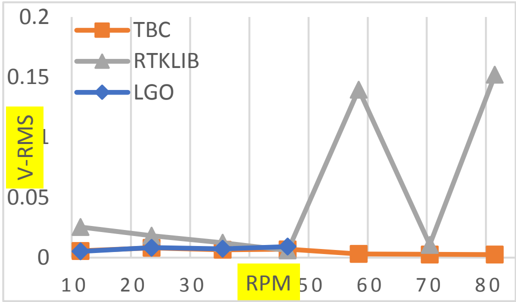


**Figure 2: The effect of processing software on the**

B)




**accuracy. a) For horizontal accuracy at rotation radius 45 cm and short baseline. b) For vertical accuracy at rotation radius 30 cm and medium baseline. Unit of RMS is……**

The following observations regarding the processing software effect were noticed:

- LGO has processing limitations for data collected at RPM higher than 47 in all tests. On the other hand, the resolved coordinates have good precision without outliers.
- TBC could resolve the integer ambiguities for all tests with the best precision in all three tested packages. However, not all the observed points were resolved, especially for tests conducted at the highest speeds
- RTKLIB resolves the ambiguity of all tests too, but with the lowest precision compared to the other two packages as it had many outliers.

To further compare the software packages, analysis of variances test (ANOVA test) was carried out to check if there is a significant difference between the software packages. The following conclusion was reached: No significant difference between LGO and TBC software packages was found. However, there is a significant difference between them and RTKLIB especially at high speeds.

**Table 4: Percentage of solved and outlier points for each software**

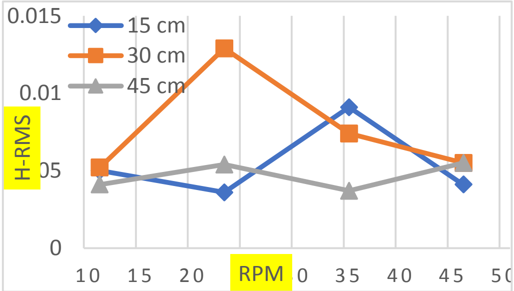
| | Percentage of solved points | | | Percentage of outlier points | | |
|---|---|---|---|---|---|---|
| | LGO | TBC | RTKLIB | LGO | TBC | RTKLIB |
| ≤47 RPM | 93.4 | 93.83 | 90.7 | - | - | - |
| >47 RPM | - | 13.98 | 44.69 | - | - | 12.4 |

In conclusion, TBC gave the best RMS values. However, its ability to solve points decreased dramatically after the critical value (47 rpm) as shown in table 4. Before this critical value, the differences between the three software packages were very small. On the other hand, after this critical value, LGO failed to solve any observed points while RTKLIB resolved the ambiguity for all tests but with the lowest precision.

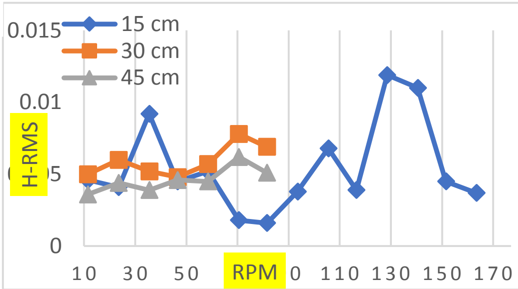
**II. The effect of changing the radius of rotation**

Sample graphs were plotted in figure (3) to show the

A)




B)




effect of changing rotation radius on results accuracy. However, the rest of the graphs show the same behavior.

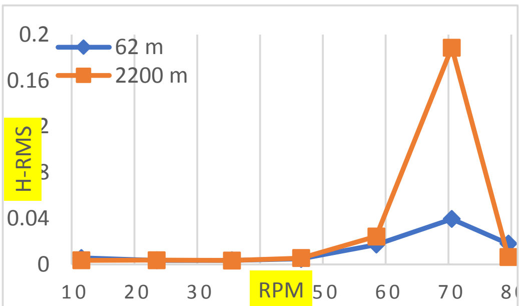
**Figure 3: The effect of rotation radius on the receiver accuracy. a) For horizontal accuracy at medium baseline and processing by LGO. b) For horizontal accuracy at medium baseline and processing by TBC.**

The results showed no correlation between observations obtained on different rotation radii. Also statistical study using ANOVA test was conducted. It revealed that changing radius of rotation, within tested limits, has no significant effect.

**III. The effect of changing the baseline length**

Sample graphs in figure (4) show the effect of changing baseline length on the accuracy., The rest of the graphs show the same behavior.

(a)




(b)

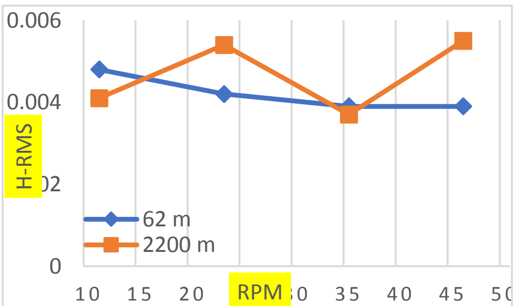


**Figure 4: Effect of baseline length on accuracy.**
**(a) For horizontal accuracy at rotation radius 45 cm and processing by LGO.**
**(b) For horizontal accuracy at rotation radius 45 cm and processing by RTKLIB.**

The results showed no correlation between observations obtained on different baseline lengths. Also statistical study using ANOVA test was conducted. It revealed that changing baseline length within tested limits has no significant effect.

### V. The effect of changing the speed of rotation

To account for the resultant RMS value at each RPM, the pooled standard deviation was calculated [8]. This data is plotted in figure (5).

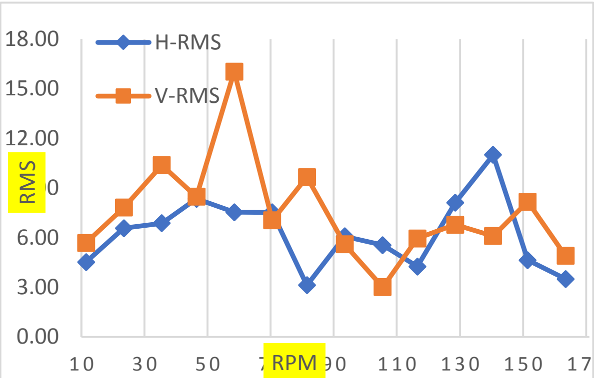



**Figure 5: GNSS receiver accuracy with RPM variation.**

Since the main purpose of this research is to study the behavior of GNSS receivers in highly dynamic applications, it is important to investigating the relation between the vertical and horizontal accuracy at different speeds

**(b) RTK processing mode**

In RTK mode, a radio link was initialized between the two receiver's units. Thus, the positions of the rover unit may be computed instantaneously. The maximum speeds at which RTK initialization get lost at different rotation radii and baselines were detected (table 5) and the corresponding accuracy was calculated (table 6).

**Table 5: Maximum speeds for different rotation radii and baselines lengths during RTK mode**

| RTK Mode Test | Short baseline (62 m) | | Medium baseline (2200 m) | |
|---|---|---|---|---|
| | Km/h | RPM | Km/h | RPM |
| 45 cm radius | 11.88 | 70 | 11.088 | 65.33 |
| 30 cm radius | 9.24 | 81.67 | 8.448 | 74.67 |
| 15 cm radius | 7.26 | 128.33 | 6.6 | 116.67 |

These speeds are the arithmetic average of these trials and are within + 5 RPM tolerance. It is important to mention that if the receiver was started rotating with a maximum speed directly, the RTK will not initialized. In other words, to reach a maximum speed, first, the GNSS receiver must start rotating with lower speed then begin to accelerate until reaching it.

The effect of changing the baseline length on accuracy was investigated as shown in figure (6).

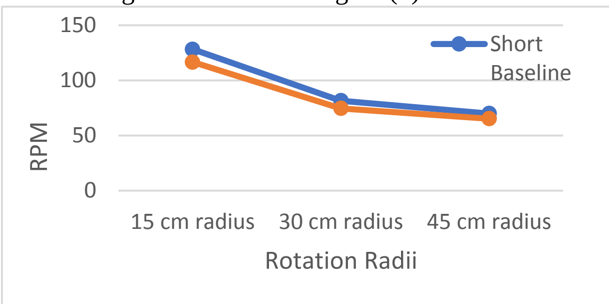



**Figure 6: Baseline length effect on maximum rotation speeds for different radii during RTK mode**

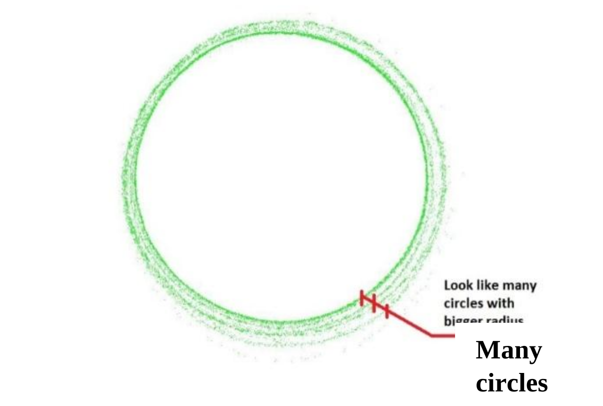
It was noticed that there is a decrease in maximum speeds accompanied with the medium baseline. This is mainly because the radio connection signals traveled longer to reach the rover unit and faced more obstacles. However, this decrease is small because short and medium baselines are small compared to signal's speed.

The accuracy of the measurements for different baselines and rotation radii is listed in table 6.

**Table 6: RMS values of horizontal and vertical coordinates measured on each rotation radius and baseline in RTK mode.**

| Rotation Radii | Short baseline(62 m) | | Medium baseline (2Km) | |
|---|---|---|---|---|
| | H-RMS (mm) | V-RMS (mm) | H-RMS (mm) | V-RMS (mm) |
| 45 | 24.8 | 76.6 | 25.2 | 32 |
| 30 | 17.6 | 10.9 | 19.3 | 10.9 |
| 15 | 21.3 | 18.6 | 11.3 | 15.6 |

It was noticed that wind-up effect caused significant amount of error in the data as shown in figure 7. This happens when the receiving antenna undergoes significant rotation inducing an observed frequency shift and causing the receiver to have problems acquiring and maintaining lock [9].




**Figure(7): Carrier phase wind-up effect on collected data at different rotation speeds during RTK mode**

## Conclusions

Based on the results and analysis of the data obtained from the conducted tests at different testing techniques and different observation mode, GNSS systems are highly recommended for use in monitoring applications in high dynamic modes. However, the following remarks may be concluded:

**I. Post Processing Mode**

1. The maximum speed reached before losing locking was 13.464 km/h (3.74 m/sec) at 45 cm rotation radius while the maximum RPM was 175 rpm at 15 cm rotation radius.
2. The horizontal accuracy (RMS) was in the range from 3 to 11 mm and the vertical accuracy (RMS) was in the range from 3 to 16 mm. This is compatible with the device specifications (Leica Viva GS 15) listed in the data sheet which states that <u>the accuracy of the receiver (RMS) in kinematic with post processing is 8 mm + 1 ppm in horizontal and 15 mm + 1 ppm in vertical.</u>
3. TBC gave the lowest error values. However, its ability to solve points decreased dramatically after the critical value (47 rpm). Before this critical value, no significant difference was found between the three packages. While after this critical value, LGO failed to solve any observed points and RTKLIB resolved the ambiguity for all tests but with the lowest precision.
4. Changing the baseline length from short to medium has no significant effect on the obtained accuracy. Also the change of rotation radius within tested values has no significant effect on accuracy.

**II. RTK Mode**

1. The maximum speed reached before RTK initialization is lost was 11.88 km/h (3.3 m/sec) at 45 cm rotation radius while the maximum RPM was 128.33 at15 cm rotation radiu.
2. The horizontal accuracy (RMS) was in the range from 11 to 25 mm and the vertical accuracy (RMS) was in the range from 11 to 32 mm, except for one trial which gave 76 mm for vertical component.
3. The device specifications (Leica Viva GS 15) listed in the data sheet states that the accuracy of the receiver (RMS) with Real Time kinematic is 8 mm ± 1 ppm in horizontal and 15 mm ± 1 ppm in vertical. These values are not compatible with the present research results because of the accumulative nature of error due to testing criteria.

**Recommendations for Future Work**

- Since the results are greatly dependent on the used hardware (GNSS receiver), it is recommended to test other commercial receivers to assess the effect on accuracy. It is recommended also to further investigate more processing software packages.
- The used GNSS receiver was eligible to receive signals from GPS and GLONASS only. It is recommended to investigate the effect of receiving additional signals from new constellations such as Bediou and Galileo or any other new systems when they become available.

## References

[1] Chao, H., Y. Cao, and Y. Chen, "Autopilots for small unmanned aerial vehicles: a survey," *International Journal of Control, Automation and Systems,* vol. 8, pp. 36-44, 2010.

[2] Bock, Y., L. Prawirodirdjo, and T. I. Melbourne, "Detection of arbitrarily large dynamic ground motions with a dense high-rate GPS network," *Geophysical Research Letters,* vol. 31, 2004.

[3] . Im, S. B., S. Hurlebaus, and Y. J. Kang, "Summary review of GPS technology for structural health monitoring," *Journal of Structural Engineering,* vol. 139, pp. 1653-1664, 2011.

[4] Middleton, L. E., "Live tendon system inhibiting sway of high rise structures and method," ed: Google Patents, 1990.

[5] Nnamani, N., "Strategies for mitigating wind-induced motion in tall buildings through aerodynamic and damping modifications," Massachusetts Institute of Technology, 2012.

[6] Okorocha, C. V., and O. Olajugba, "Comparative Analysis of Short, Medium, and Long Baseline Processing in the Precision of GNSS Positioning," *Kuala Lumpur, Malaysia: FIG Congress,* 2014.

[7] Jing, S., X. Zhan, B. Liu, and M. Chen, "Weak and Dynamic GNSS Signal Tracking Strategies for Flight Missions in the Space Service Volume," *Sensors,* vol. 16, p. 1412, 2016.

[8] Hedges, L. V. and I. Olkin, in *Statistical methods for meta-analysis,* ed San Diego: CA: Academic Press, 1985, p. 79.

[9] Beyerle, G., "Carrier phase wind-up in GPS reflectometry," *GPS solutions,* vol. 13, p. 191, 2009.